

Study of Free-Free Beam Structural Dynamics Perturbations due to Mounted Cable Harnesses

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Signal and power harnesses on spacecraft buses and payloads can alter structural dynamics, as has been noted in previous flight programs. The community, however, has never undertaken a thorough study to understand the impact of harness dynamics on spacecraft structures. The Air Force Research Laboratory is leading a test and analysis program to develop fundamental knowledge of how spacecraft harnesses impact dynamics and develop tools that structural designers could use to achieve accurate predictions of cable-dressed structures. The work described in this paper involved a beam under simulated free boundary conditions that served as a validation test bed for model development.

Nomenclature

C	= system damping matrix
F	= forcing function vector
K	= system stiffness matrix
K_c	= structural damping matrix
j	= imaginary unit
M	= system mass matrix
M_c	= mass-proportional damping matrix
x, \dot{x}, \ddot{x}	= displacement, velocity and acceleration vectors
α, β	= scalar proportionality constants
ω	= natural frequency in radians/second

I. Introduction

The evolution of military spacecraft has led to structures of ever decreasing weight and specific mass values, while the requirements on both static and dynamic mechanical stability have increased dramatically for spacecraft and payloads. Structural control systems are needed to meet mission goals and, at a minimum, the design of spacecraft systems must refine structural dynamics to minimize its impact on mission performance metrics.

Experiments used to identify plant model order, poles, and gains commonly occur early in the program development, using mass simulators before the system can be fully integrated. Near the end of the

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integration and test phase, measurements are made to quantify structural dynamics with the structure “fully dressed” and demonstrate suitable workmanship levels. From the measurements on the fully dressed structure, it is commonly found that the dynamics changed from the original “bare structure” tests. Previous flight program tests have shown that flight harnesses can shift modal frequencies and cause a significant increase in modal damping ratios, particularly those at high mode order. This illustrates that a potentially critical component missed in the design and integration of precision space structures are power and signal cable harnesses.

Since it is not standard practice to include cable harnesses in modal models (with the exception of modeling harnesses as non-structural mass), it is conceivable that numerical results and designs are overly conservative, requirements for isolation systems are overstated, and high bandwidth structural control systems may be adversely affected (i.e., reduced performance with nominal gains and/or instability). Refining the controller design before launch is imperative: finding that the control system is unstable when on-station is a worst-case scenario.

The Air Force Research Laboratory-led team is studying the following aspects of cable harness effects on precision structures: the underlying physics of unsupported cables, a case study of a space telescope test bed and how cable harnesses alter the dynamics of simple and lightly damped test articles. The latter test and analysis program is covered in this paper. The overarching program goals include extending the understanding of the effects of cable harnesses on a structure’s dynamics leading to development of design tools for the structural dynamicist. Ideally, the design tools will allow the engineer to fine-tune the structural dynamics to increase on-station mission performance through harness design, placement and mounting geometry, thereby reducing conservatism in the design phase. In essence, this experimental and analysis effort will advance the technology allowing power and signal cable harnesses to be integrally designed into a spacecraft: *Why not use the harnesses to improve structural dynamics and increase mission performance?*

This paper describes a free-free beam test structure used to document the effects of cables on the dynamic response of a flexible structure. Also included are ways that the cable dynamics can be included into system models within the current framework of linear finite element modeling. Cable effects also can be reduced to structural damping coefficients and modeled as distributed lumped parameter models, as detailed in this paper. Extension of these techniques may augment active areas of applied research including model appropriateness, confidence levels and uncertainty quantification of structural dynamic measurements for precision space structures. Deterministic, stochastic and “hybrid” models may be found as appropriate modeling techniques for predicting structural dynamics of precision structures with mounted signal or power cable harnesses^{1,2}.

II. Free-Free Beam Test Specimen and Test Setup Details

A free-free beam of uniform cross section was chosen to quantify the effects of cable harnesses on a simple and modelable structure. The beam served as a test bed for model validation experiments in the synergistic test/analysis cable effects program. The nearly ideal free boundary condition was easily implemented in the laboratory; closed-form beam equations were found to agree with measurements.

The beam was designed to have a 40 Hz first bending modal frequency. The suspension mode of the test set-up with the highest modal participation factor was at 1.3 Hz. The separation between the suspension modes and first bending mode exceeds the order-of-magnitude frequency separation rule of thumb commonly used for modal testing: more than one order of magnitude between the suspension and flexible body modes assures that suspension modes do not couple strongly with the flexible body modes.

Low base structure damping was a design goal to assure that measured damping ratios with a cable mounted to the structure dominated the loss mechanisms. In addition, nonlinear design features (such as mechanical joints) were avoided to simplify analysis and allow straightforward estimation of harness nonlinear effects, if they exist. The beam was designed to have a base structure-to-cable mass ratio commensurate with mass ratios on Department of Defense (DoD) spacecraft. Harness-to-structure mass ratios are commonly in the four-to-twenty percent range for spacecraft, as determined in an industry and literature survey early in the cable effects program. This mass ratio range was adopted in the experiment plan and used for cable harness construction design.

Figure 1 shows the excitation setup and the test article suspended on long cords in the laboratory. An electrodynamic shaker and a piano wire stinger were used to provide controlled, band-limited excitation. A

high sensitivity piezoelectric load cell measured the disturbance. Structural response was measured using either a single-point laser vibrometer or accelerometer at the driving point. The majority of the measurements utilized the vibrometer resulting in mobility frequency response functions (FRFs) with no influence of sensor wiring. Sampling and digital signal processing to acquire frequency response functions utilized a VXI-based data acquisition system. Signal types included continuous and burst random waveforms.

Structural dynamic parameters, including natural frequencies, damping ratios and modal mass were estimated from measured frequency response functions. Figure 2 shows a typical driving point inertance FRF measured on the bare beam (i.e., with no cable harness attached). Modal damping ratios are very low and the resonant frequency spacing agrees with the closed-form relationship. The driving point location was chosen to increase the modal participation factors for the third and fourth modes and limit those in the first two modes, as depicted in the figure.

Figure 3 shows this driving point FRF in the Nyquist plane, near the bare beam first bending mode. Natural frequency and damping ratio results are displayed with calculated parameters of the least squares fit of a circle to the frequency response function. Spectral lines in the measurement are shown with blue circles and the least squares circle fit is shown in a magenta solid line texture. The estimated natural frequency is shown with a green diamond and the “half-power points” used to determine the modal damping ratio are shown with the red diamonds in this figure. The light damping is evident and consequence of leakage on the measurement is evident from the distortion near resonance. The circle fitting algorithm was used extensively in the analysis of the beam FRFs due to the high degree of user interaction in the parameter estimation process that allows the engineer to reduce the parameter estimation errors. This technique was also used to extract cable harness test article modal parameters in the lateral “cable only” testing in another part of the cable effects program³.

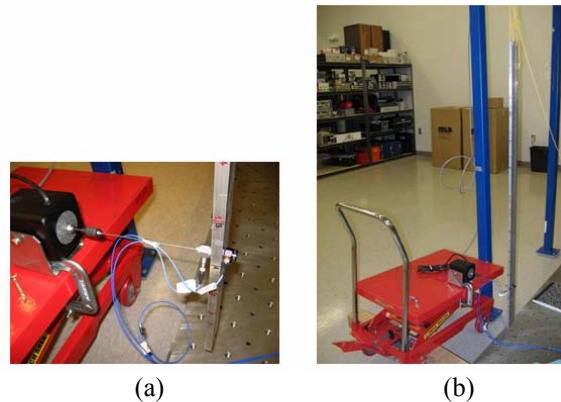


Figure 1 Exciter set-up (a); test article configuration (b)

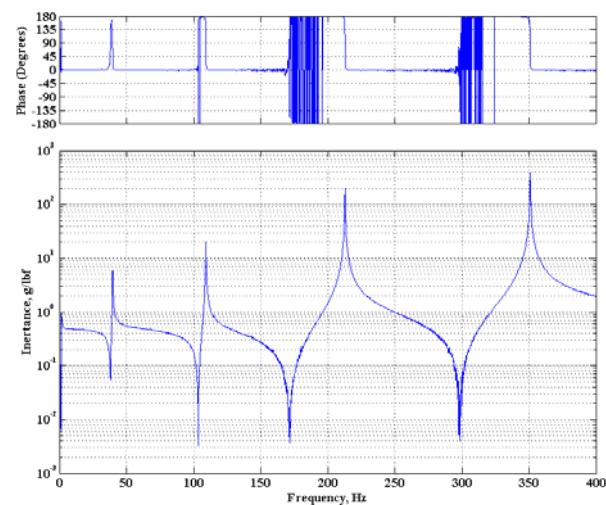


Figure 2 Bare beam inertance frequency response function

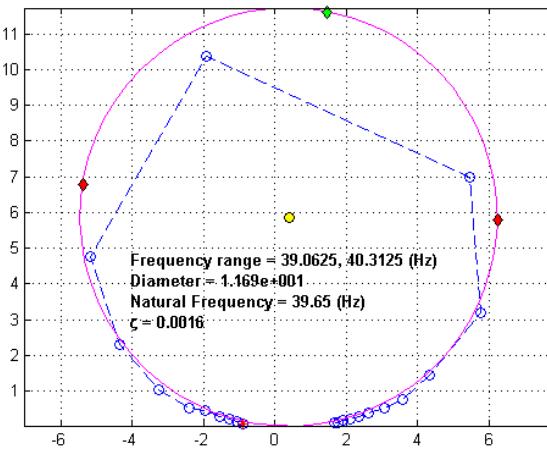


Figure 3 Bare beam Nyquist plot around 1st bending mode
 American Institute of Aeronautics and Astronautics

III. Cable Construction and Mounting Details

Cable harness construction and mounting techniques adhere to good engineering practices followed in the spaceflight industry, standards, and harness construction recommendations that appear in the literature⁴. Cables were made from twisted pair single-conductor wires with Teflon insulation, per MIL-W-22759/11, “stitched” with lacing cord and encapsulated with a Kapton tape wrap. Figure 4 shows details of cable construction. The cables did not include terminating connectors or strain relief provisions.

Adhesively mounted tabs and lacing cord or cable ties were used to attach the cable to the beam, as is commonly done in spacecraft integration applications. In this series of experiments two sets were positioned on the beam: one along its centerline, the other set allows for a “serpentine” mounting pattern. Figure 5 shows mounting details, including examples of the “straight” and “serpentine” lacing pattern. The mounting tabs were installed with four-inch spacing and provide a small standoff distance between the harness and the back-up structure. This attachment method prompted simple beam analysis models for the cable, connected to the beam at the tie down points, as described in following sections.

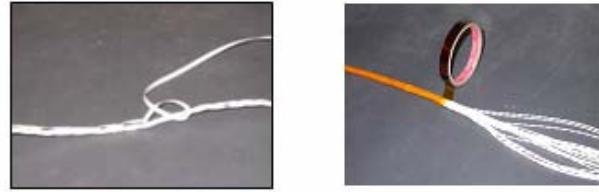


Figure 4 Cable construction: (a) lacing; (b) Kapton wrap



Figure 5 Cable harness mounting details:
 (a) straight configuration; (b) serpentine configuration;
 (c) attachment elevation view

IV. Harness-on-Beam Measurements

Mobility and inertance frequency response functions at the driving point location were used exclusively in this test series to demonstrate the influence of a harness mounted to the lightly damped aluminum beam. Because modal damping ratios and natural frequencies are global properties, driving point measurements are sufficient to illustrate perturbations to the beam dynamics resulting from the harness mounted along the beam.

Figure 6 shows driving point inertance point inertance frequency response functions, in Bode plot format, measured under two conditions: the beam “bare” and with a harness mounted with a straight pattern along the length of the free-free beam. Changes to the structural dynamics, caused by the cable harness, within the 800 Hz measurement band width, are clearly evident. In the low frequency range (below the beam’s third mode) there is little effect. At the third mode, the harness causes a noticeable decrease in resonant frequency (i.e., mass

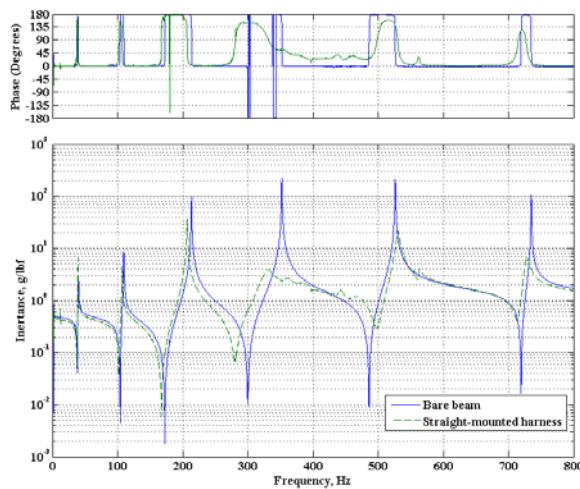


Figure 6 Bare beam and straight harness inertance functions

loading), and an increase in modal damping ratio. The fourth mode, near 350 Hz, is dramatically affected, with a decrease in the quality factor by roughly two orders of magnitude. Quality factors in the fifth and sixth modes decrease roughly an order of magnitude: the modal damping ratios increase by approximately a factor of five in these modes.

A comparison of inertance FRFs for straight and serpentine cable configurations appears in Figure 7. The responses of the beam with the two harness mounting configurations are similar, with the noticeable difference being higher damping in the modes above 500 Hz. The harness interacts strongly with the base beam structure in the 300-to-400 Hz range for both the straight and serpentine tie-down configurations.

Measurements were made to document the influence release of harness extensional tractions on system dynamics by removing the last tie at each end of the harness in a straight lay configuration. This data, plotted with the straight harness mounting is shown in Figure 8. The two inertance functions illustrate similar dynamics, except in the vicinity of the 40 Hz first bending mode. Inspection of these FRFs shows evidence of a mode coupled to the first bending mode, as shown in the expanded view in this figure. Explanation of this behavior is being studied. The hypothesis is that the harness free ends, being cantilevered, have high compliance and result in bending resonances close to the beam first bending mode. The strong coupling is thought to be caused by high modal response near the last tie positions.

FRF sensitivity to tie-down spacing also was evaluated. Two tie-down configurations of the straight cable, illustrated in Figure 9, were investigated. The measured FRFs are shown in Figure 10. The change from four-inch to eight-inch spacing has a marked effect on the FRF. Modal peaks are reduced above the first mode more consistently. The FRF from the “88444488” configuration is qualitatively similar to the uniform eight-inch spaced configuration.

These data show that a lightweight harness (the harness-to-beam mass ratio was roughly 8%), affects the system dynamics in the following ways.

- At low frequencies the modes shift slightly due to a mass loading;
- At high frequencies, the harness increases the system modal damping ratios;
- Cable dynamics that strongly couple with base structure modes can result in dramatic reduction in the system quality factors.

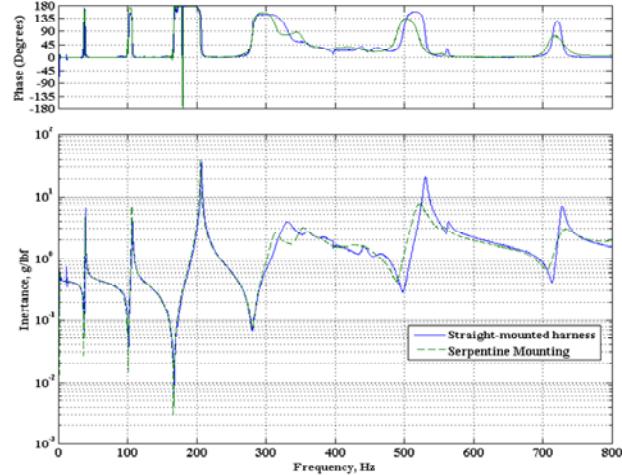


Figure 7 Inertance FRFs - straight and serpentine mounting

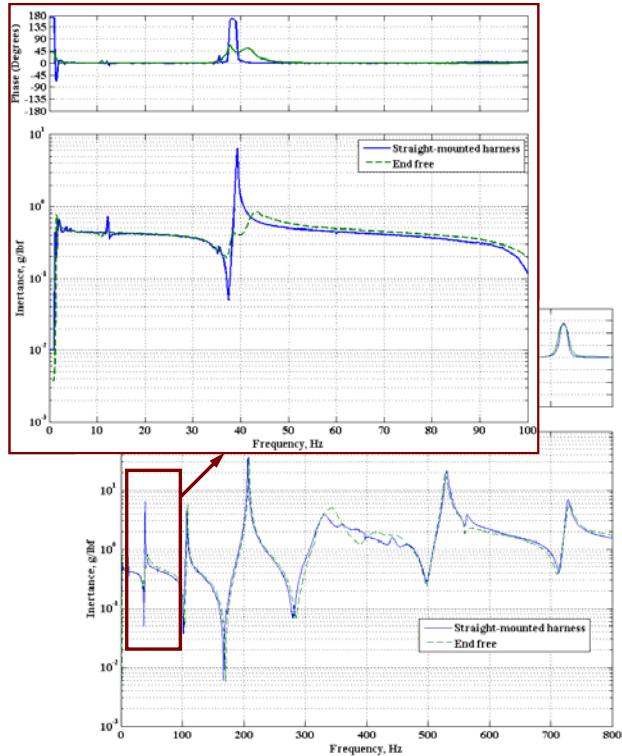


Figure 8 FRFs showing effects of loose harness ends

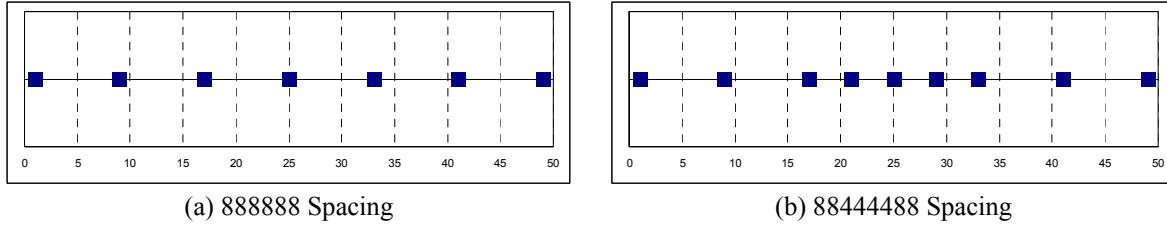


Figure 9 Tie-down spacing configurations

These observations indicate that a modeling approach must account for the frequency-dependent behavior of the cable on the base structure. Overly simplistic models would result in large errors predicting the system dynamics, and produce inaccurate estimates of control system performance and closed loop stability. Appropriate model formulation, benchmarking harness effects with linear finite element models and a study of the impact of neglecting cable effects on high-authority controllers (due to plant errors) are being studied in other phases of the program.

V. Lumped Parameter Model Formulation

In the industry, when harnesses are included in finite element models, the practice is to use a non-structural mass approach. While this is useful in benchmarking the system-level mass budget, it is clear from data on previous flight programs and the free-free beam measurements that the dynamics of a “dressed” structure will not be predicted accurately using this simplistic technique. On the beam test article, for example, one would expect that a finite element model could correctly estimate the low frequency dynamics (up to 200 Hz) with some level of accuracy, have large errors at high frequencies where loss mechanisms are significant, and be orders of magnitude off at frequencies where the structure modes couple with cable resonances. In short, the practice of using non-structural mass is appropriate at best in the frequency range below where the cable harness becomes resonant, above that frequency range the inaccuracy can be very large.

To assist in the cable model development, the behavior of a simple Euler beam was studied using a linear finite element model (FEM). The underlying assumption was that a cable can be approximated by a beam in bending. The initial goal in this study was to determine if a linear beam finite element model is appropriate for a cable harness, by benchmarking the model results with “cable only” lateral dynamic measurements. The beam finite element model was built with “slider” end conditions: having only one degree of freedom released in a beam lateral direction; a 5% viscous damping ratio for all modes; a lineal mass like that of a cable specimen, and a first modal frequency commensurate with the measured cable

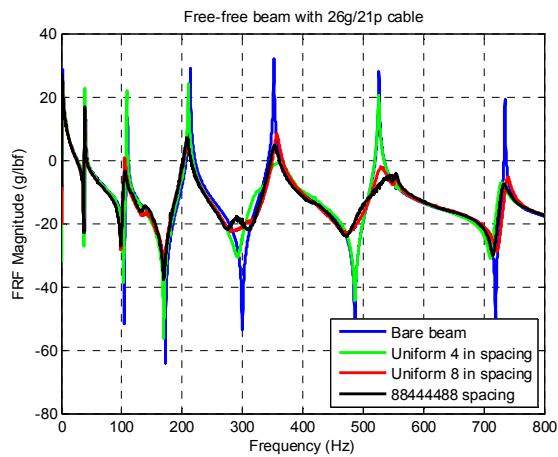


Figure 10 Comparison of tie-down spacing effects

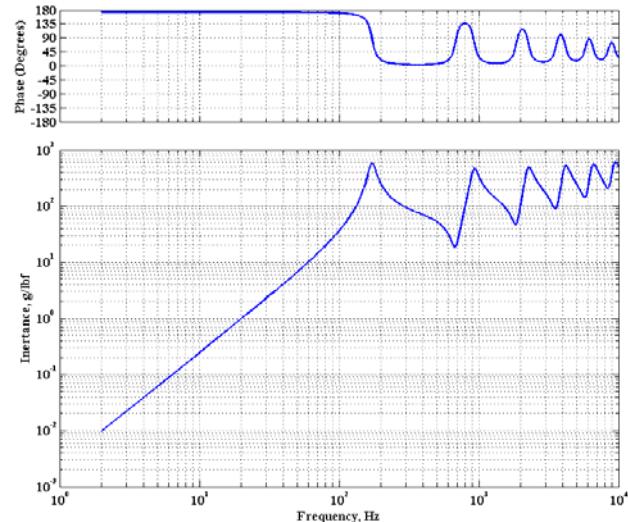


Figure 11 FEM beam driving point inertance FRF

dynamics similar to test. Figure 11 shows the driving point inertance FRF, simulated with the finite element model. The resonant frequency progression follows the quadratic relationship in elementary beam theory.

Figure 12 shows an inertance FRF computed from a measured driving point mobility function on a harness under clamped-clamped boundary conditions. The similar appearance between the beam prediction and the measurement indicates that the cable is “beam-like” under lateral dynamic loading. Cable harness measurements under different simulated boundary conditions have shown that driving point inertance functions under different boundary conditions (e.g., simulated pinned-pinned, clamped-clamped and ends secured with cable ties) have the same trends as that shown in this figure: the resonant frequency spacing is affected, but the slope of the stiffness line is boundary condition-invariant.

Figure 13 depicts two synthesized inertance FRFs: one has the natural frequency spacing for a simple Euler beam; the other frequency response function is based on a measured cable frequency progression. These functions are sums of single degree of freedom (SDOF) systems; each mode is the inertance between the response of the suspended mass and a co-located force acting on the mass. Thus the cable driving point frequency response function is similar to the sum of SDOF inertance functions when driving the cable’s effective mass with a spring and viscous damper to ground (i.e., the mass is driven, not the base of the spring).

Dynamic interaction with the cable may have “tuned mass damper-like” behavior, similar to that observed in the beam tests, however the cable harness is not a notional tuned mass damper (TMD) where the spring and dashpot are between the structure and suspended mass (i.e., the SDOF base is driven, not its mass). For a TMD, the low frequency asymptote is horizontal with a value of the reciprocal of the suspended mass; in the cable measurements the low frequency asymptote instead has a slope determined by the harness stiffness. The discrepancy in the frequency spacing illustrates a limitation of using beam models for predicting dynamics due to cable harnesses: a cable has a higher modal density than a pinned-pinned beam.

Figure 14 shows two inertance functions on the same axes: one computed from a “cable only” mobility measurement, the other is simulated by four SDOF oscillators, using 5% viscous damping and the identical effective mass in each mode, and the measured frequencies. The close agreement between the measurement and the synthesized FRF has a far-reaching implication for cable model development and implementation in the spaceflight structures community. The cable model can be simple and follows standard structural dynamic models for linear structures. One goal of the cable effects applied research was to determine if cable harnesses can be simulated using simple and deterministic models. The results from the cable lateral tests indicate that this is indeed the case. Additional study is required to determine if such a model breaks

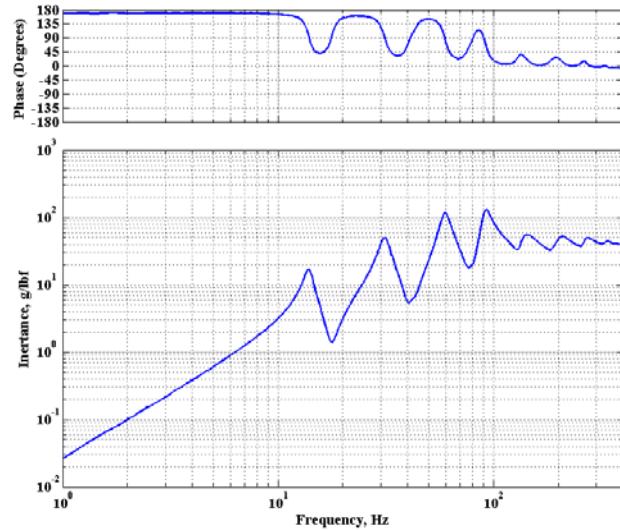


Figure 12 Cable driving point inertance

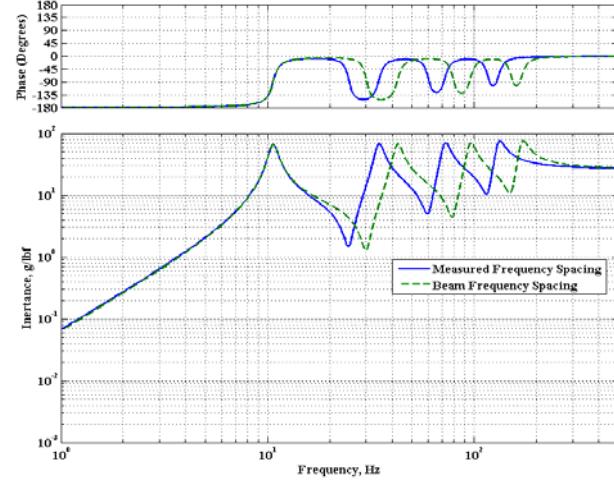


Figure 13 Inertance FRFs with pinned-pinned Euler beam and measured resonant frequency spacing

down at extreme mode number and determine if a stochastic or “hybrid” deterministic/stochastic model is required.

The simple lumped parameter model formulation offers attractive options for simulation to spacecraft design and structural control teams. Implementing lumped parameter models in a finite element model is possible, as an obvious extension to the non-structural mass technique. This approach holds the promise of allowing structural engineers to “design-in” harness routing to benefit system dynamics.

The cable lumped parameter model also could be used in a context of either test or analysis-based technique using either frequency response functions directly or in a state matrix formulation. The former is attractive if the cable model can be shown to accurately predict the influence on performance metric frequency response functions. For example, an advancement to spacecraft structural design technology would be the ability to predict the impact on imaging sensor jitter-to-noise source FRFs measured early on in flight programs before harnesses are designed and integrated on the spacecraft. Development of a framework to implement the structural modification in a state equation formulation could fit the need between the finite element model and the controls team and may provide an avenue to refine both harness routing for benign system dynamics and increase the accuracy in the control simulations. Study of implementing cable dynamics in a lumped parameter formulation similar to distributed tuned mass dampers^{5,6} as appears in the literature, is in process; the free-free beam test article is being used as a test case.

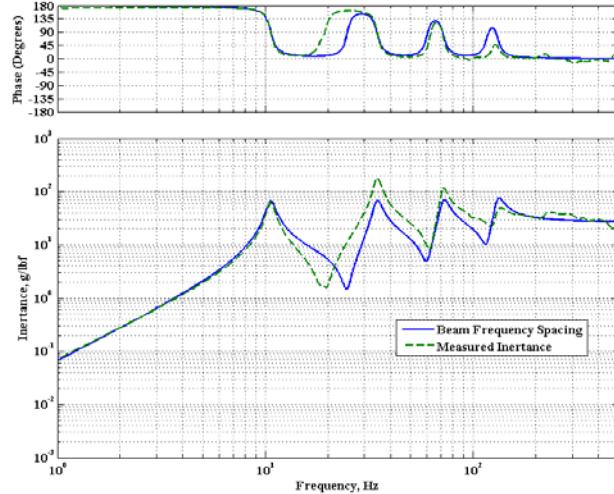


Figure 14 Measured and synthesized inertance FRFs

VI. Finite Element Modeling

As discussed above, experience has shown that cables affect the dynamics of the underlying structure in at least two ways at “high” frequencies. They add damping and they dynamically interact, often in dissipative ways with the underlying structure. The next section discusses ways to represent the additional damping cables provide in a finite element model. Dynamic interactions are discussed in the subsequent section, followed by a discussion of finite element modeling approaches.

A. Damping Models

Modal Damping

The standard approach in the satellite industry is to create a finite element (FE) model from which mass and stiffness matrices are obtained. Modal damping is assigned based on experience and perhaps program requirements (which are also experience based). Then performance models (for jitter and pointing control, wavefront errors, etc.) are created and exercised. Consequently, one approach is to simply assign increasing modal damping ratios with frequency. For example,

Frequency Band	Modal Damping Ratio
0 – 50 Hz	0.25 %
50 Hz – 150 Hz	0.5 %
150 Hz – 300 Hz	4 %
> 300 Hz	7 %

While simple and straightforward, such an approach is only partially satisfying because modal damping is not physical – it is an artifact of analytical convenience that has been shown to be sufficiently accurate for many lightly damped structures – and therefore any damping ratio distribution would have to be based

on empirical data, which do not currently exist⁴. Furthermore, such a damping assignment always would be more subject to programmatic arguments than a physically grounded approach.

Structural Damping

Another straightforward approach is to use a damping matrix proportional to the cable stiffness or mass, in addition to modal damping. The basic form of the dynamic equations is:

$$\begin{aligned} M\ddot{x} + C\dot{x} + (jK_c + K)x &= F \\ K_c &= \beta K \end{aligned} \quad (1)$$

for structural damping, and

$$\begin{aligned} \left(M + \frac{M_c}{j} \right) \ddot{x} + C\dot{x} + Kx &= F \\ M_c &= \alpha M \end{aligned} \quad (2)$$

for mass-proportional damping. In both cases, the scalar coefficients (α and β) must be chosen appropriately. Strictly speaking, these forms of damping only apply to frequency domain analyses since a complex stiffness (or mass) matrix is not physically realizable without some active elements. Mass proportional damping also includes a frequency weighting term that is not present in structural (stiffness proportional) damping. Structural damping can be approximated with a real damping matrix which leads back to effective modal damping.

Figure 15 shows a model derived driving point FRF for a cantilever beam with structural damping. The qualitative behavior of the FRF is consistent with the experimental data on the free-free beam. The main issue with this approach is determining an appropriate complex stiffness matrix from the cable properties. This requires knowledge of the cable harness properties (i.e., cable stiffnesses). Some insight can be gained from theory because β is related to the damping ratio and frequency by the following formula, $\beta = 2\zeta/\omega$, where ζ is the damping ratio and ω is the natural frequency in circular frequency units. For example, if one desires 3% damping at 1000 Hz, then β equals approximately 1e-5.

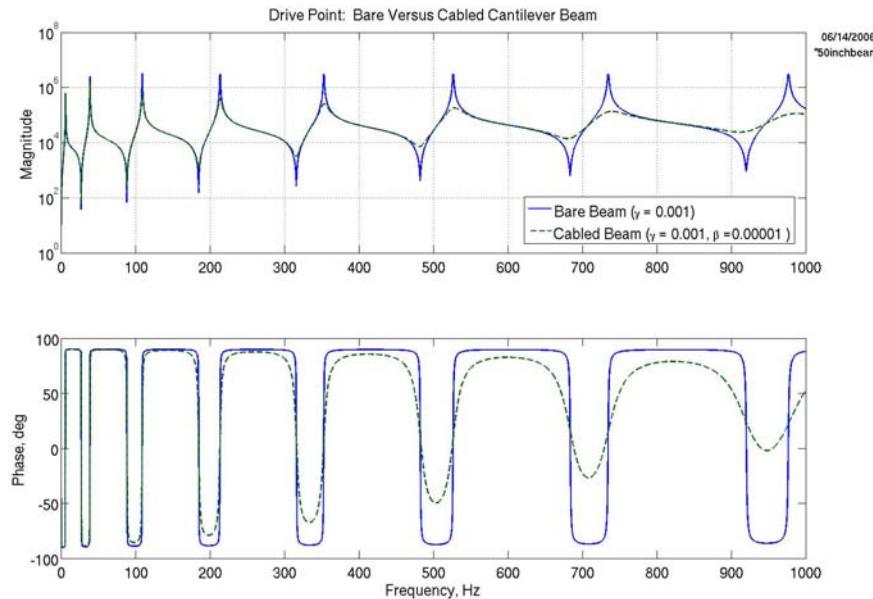


Figure 15 Cantilever Beam FRF with Modal & Stiffness Proportional Damping

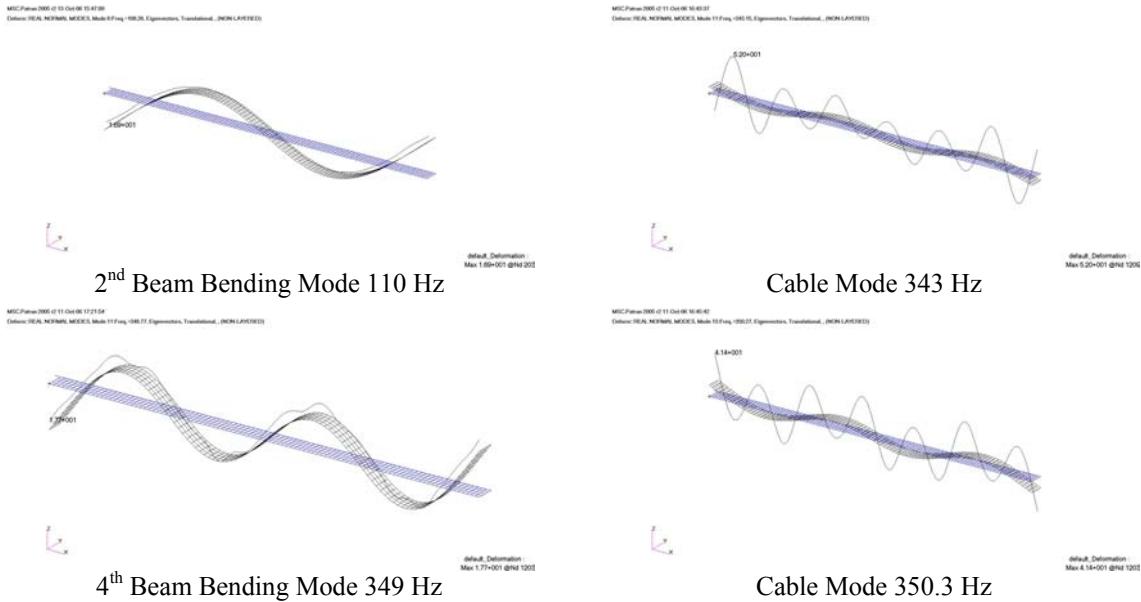


Figure 16 Interations of Cable and Beam Modes

B. Structural Interaction

Dissipative cable effects have been observed at frequencies where the cables are resonant. Figure 16 shows two mode shapes of a free-free beam. At mode 2 the modal participation from the cable is minimal. Around mode 4 the cable participates significantly. There are cable modes around the fourth beam mode that affect the frequency response. For the beam experiments, it was possible to predict the cable's resonant lower bound using a multi-span beam model of the cable. For more complex structures, it is unlikely that a purely analytical method will be sufficient to predict the structural interaction boundary and modeling approaches will need to be developed.

Above the interaction boundary, cable damping and interaction with the structure affect the system response. If cable modes are closely coupled with the underlying structure's modes, energy transfer will occur and the cable may act as a damper. This is almost certain to occur on modally dense structures, but these types of interactions are sensitive to the properties of the cable (modulus, mass, and damping) and structure. Figure 17 shows FRFs of the cabled free-free beam generated with MSC.Nastran SOL 111 for different cable Young's modulus values (E is constant) and damping levels. Also shown in the figure is a measured FRF. The shape of the FRF depends on the value of EI . At the smallest EI , the modal response at modes 3 and 5 is reduced by the interaction of the beam and cable. The model FRF synthesized with the largest EI fairly represents the measured FRF in which only the fourth beam mode is affected. This figure shows the need for reliable cable stiffness and geometric properties. Modeling cabled structure response only with higher levels of modal damping without considering the dynamic interaction of cable and structure is insufficient. Whether this dissipative dynamic interaction can be accurately predicted with models on complex structures and practically exploited is still under investigation.

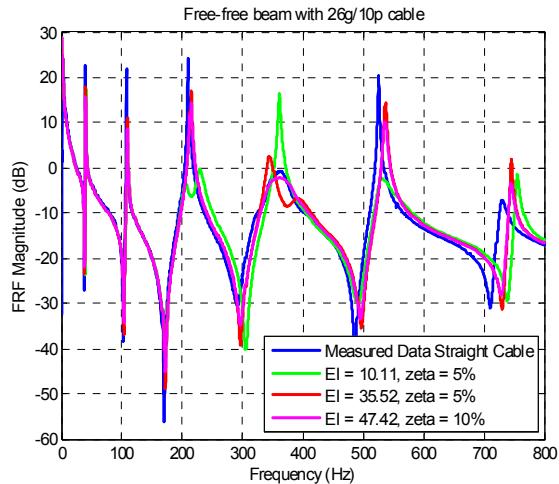


Figure 17 Model generated FRFs with various cable stiffnesses

C. Finite Element Modeling of Cabled Structures

One of the main objectives of the cable effects program is to evaluate whether the contributions of cable harnesses can be represented within the general framework of linear analysis. The desire is to be able to include harness models in standard (linear) spacecraft structural models, without having to resort to non-linear modeling.

As part of the Air Force Research Laboratory research effort, cables were tested to determine their structural properties. It was found that damping levels are input amplitude dependent, i.e., cables are non-linear elements. At low input levels, commensurate with modal test and expected on-orbit disturbances, the effective modal damping seems to be between 3% and 6% almost independent of frequency³. Also, at low input levels the cables may be approximated as beams, rather than tension elements. Bigger cables were better represented by the beam assumption than small ones. This indicates that perhaps there is a lower bound on cable size that can be reasonably modeled and analyzed with linear tools.

Clearly the cable harness must be included as a structural component in a finite element model. One way to do this is to represent the cables as beams, pinned at the tie-down points. The pinned connection to the structure can be represented with an RBE2 connection in which the rotational degrees of freedom are left unrestrained. Since the cable has greater damping than the bare structure and cable damping properties can be measured and tabulated, it is desirable to associate higher damping with the cable elements rather than the entire structure. If using MSC.Nastran, a structural damping coefficient may be included on the material property card. This approach implements the structural damping model discussed above.

Alternatively, the cable harness may be represented as a super-element (if the FE code supports super-element analysis) with modal damping assigned at the component level. For the free-free beam, the model generated FRFs are very similar – independent of the damping approach, as illustrated in Figure 18.

Finite element models of precision spacecraft usually are the basis for performance models. These models are used by other groups (e.g., control systems, systems engineering), and are created from mass and stiffness matrices extracted from the FE model. With cables included in the models, a damping matrix must also be provided to users.

Other parameters that influence the measured response of cabled structures are the tie down spacing and the rotational stiffness of the connection. Tie-down spacing is a relatively easy parameter to get right in FE models as illustrated in Figure 19.

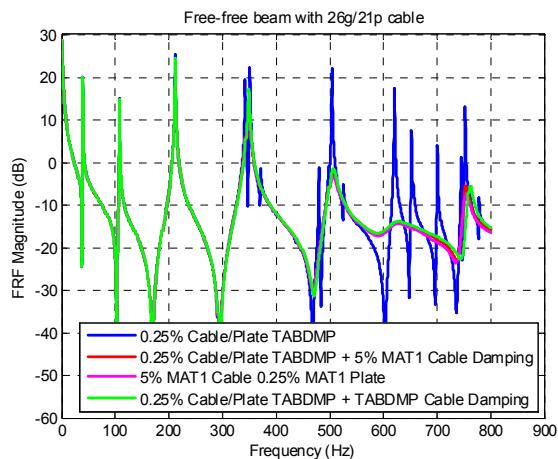


Figure 18 FE generated FRFs with various cable damping

VII. Summary

A test series was conducted using a flexible beam under simulated free-free boundary conditions with the following goals.

- Document the influence of mounting a cable harness on a flexible structure, with a mass ratio similar to those on DoD spacecraft;
- Assess the relative importance of mounting parameters such as tie-down spacing and routing (i.e., straight or serpentine) on the combined system dynamics;
- Provide a test bed for validating modeling approaches.

The measurements demonstrated that a cable harness with eight percent of the base structure mass has a frequency-dependent impact on structural dynamics that would not be accurately represented using non-structural mass in a finite element model. At low frequencies (below the harness first resonance), the resonant frequencies decrease due to mass loading. Above the harness fundamental resonant frequency, two

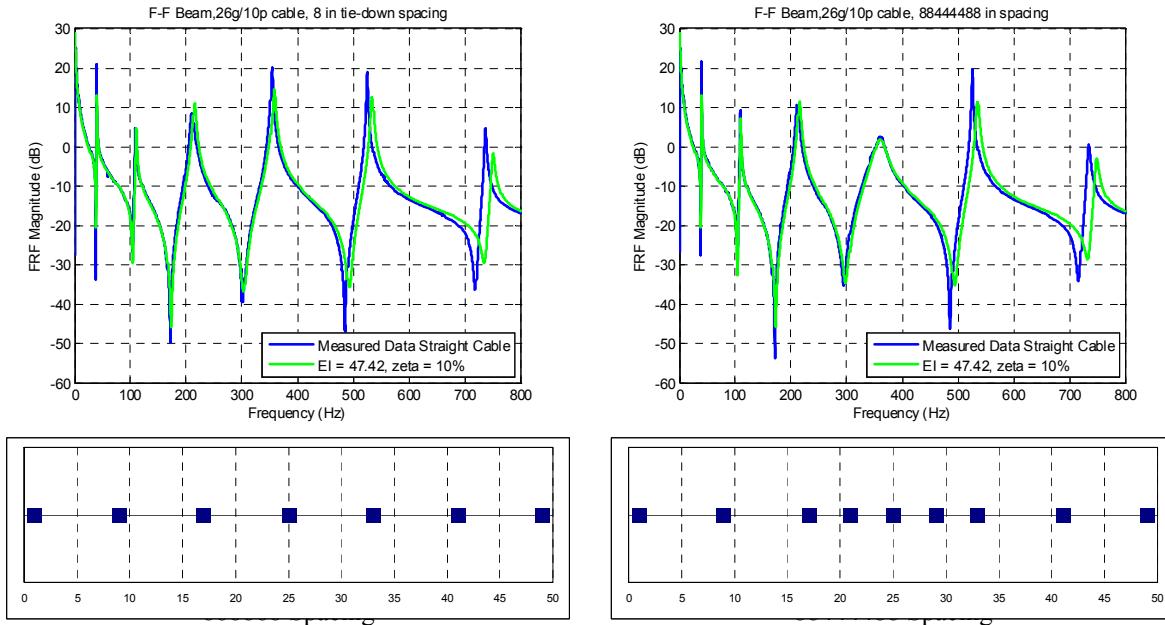


Figure 19 Driving point FRFs with variable tie down spacing

effects were observed: increased modal damping when the structure and harness modal frequencies are not coincident and a strong “TMD-like” effect if the base structure and harness resonant frequencies are the same.

Leveraging “cable only” dynamic measurements from another phase of this research, a lumped parameter model approach has been shown to closely replicate cable harness dynamics. The model formulation can replicate the natural frequency progression observed in test and is a summation of single degree of freedom systems, relating the driving point dynamics with the spring and damper connected to ground. It holds promise for integrating into finite element models, as an extension to the commonly used non-structural mass approach to modeling cable harnesses, and use in an admittance model operating on either measured or synthesized frequency response functions directly.

Finite element models of cables were investigated for modeling the “dressed” beam. Good FRF agreement was observed with test data. Higher modal damping may be assigned to the cable only and cable models may be combined with the bare structure model relatively easily. Correctly capturing the modal interactions in the FRFs depends on good estimates of the cable properties. The FRFs were more sensitive to these cable properties than to cable modal damping levels. This shows the potential complexity of modeling cabled structures and the need for validated cable properties. Future efforts will extend the modeling assessments to more parameters such as cable tie-down rotation stiffness and the modeling techniques to more complex structures.

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